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SYSTEMATIC REVIEW

EXERCISES THAT FACILITATE OPTIMAL HAMSTRING AND QUADRICEPS CO-ACTIVATION TO HELP DECREASE ACL INJURY RISK IN HEALTHY FEMALES: A SYSTEMATIC REVIEW OF THE LITERATURE.

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ABSTRACT

Background: Anterior cruciate ligament (ACL) injury is common among females due to many anatomic, hormonal, and neuromuscular risk factors. One modifiable risk factor that places females at increased risk of ACL injury is a poor hamstrings: quadriceps (H:Q) co-activation ratio, which should be 0.6 or greater in order to decrease the stress placed on the ACL. Exercises that produce more quadriceps dominant muscle activation can add to the tension placed upon the ACL, potentially increasing the risk of ACL injury.

Hypothesis/Purpose: The purpose of this systematic review was to compare quadriceps and hamstring muscle activation during common closed kinetic chain therapeutic exercises in healthy female knees to determine what exercises are able to produce adequate H:Q co-activation ratios.

Study Design: Systematic Review

Methods: Multiple online databases were systematically searched and screened for inclusion. Eight articles were identified for inclusion. Data on mean electromyography (EMG) activation of both quadriceps and hamstring muscles, % maximal voluntary isometric contraction (MVIC), and H:Q co-activation ratios were extracted from the studies. Quality assessment was performed on all included studies.

Results: Exercises analyzed in the studies included variations of the double leg squat, variations of the single leg squat, lateral step-up, Fitter, Stairmaster® (Core Health and Fitness, Vancouver, WA), and slide board. All exercises, except the squat machine with posterior support at the level of the scapula and feet placed 50 cm in front of the hips, produced higher quadriceps muscle activation compared to hamstring muscle activation.

Conclusion: Overall, two leg squats demonstrate poor H:Q co-activation ratios. Single leg exercises, when performed between 30 and 90 degrees of knee flexion, produce adequate H:Q ratios, thereby potentially reducing the risk of tensile stress on the ACL and ACL injury.

Level of Evidence: 2a- Systematic Review of Cohort Studies

Key words: Anterior cruciate ligament, electromyography, hamstrings, quadriceps, resistance training

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INTRODUCTION

Anterior cruciate ligament (ACL) injuries can be devastating to an athlete. The ACL is the primary restraint to anterior translation of the tibia on the femur,[1-4] and is often injured in noncontact conditions with the foot planted on the ground.[1] It is estimated that 70-90% of ACL injuries occur without contact in situations such as rapid change of direction, landing, and deceleration.[1,3-7] Closed kinetic chain (CKC) ACL injuries are often reported with moments of reduced knee flexion angles, increased valgus collapse at the knee, and increased internal or external tibial rotation.[8] The incidence of these injuries is believed to be 1 in 3,000 with approximately 100,000 ACL injuries occurring each year in the United States.[9] Of the ACL injuries sustained in the United States annually, it is estimated that 38,000 are in females.[7] Although males have a higher overall number of ACL injuries,[5,7] females are said to be 4-8 times more likely to have an ACL injury when data is normalized for the amount of exposures.[5-7,9-11]

Many factors have been identified that place females at increased risk of ACL injury including hormonal, anatomical factors, and neuromuscular factors.[6-10] Of particular interest are the neuromuscular risk factors because they are considered to be modifiable. Decreased strength of the quadriceps and hamstring muscles,[6,10,12,13] decreased active hamstring stiffness,[6,10] delayed hamstring activation,[10] decreased knee joint proprioception,[10] and decreased hamstring: quadriceps (H:Q) ratio[13] are all neuromuscular factors that have been identified that place females at increased risk of ACL injuries.

Females are often found to be quadriceps dominant, indicating that they preferentially activate their quadriceps over their hamstrings during functional movements. This increases the tensile force placed on the ACL, increasing the risk for injury.[1,2,5,10,11,13] Co-activation of the quadriceps and hamstrings is important to provide stability to the knee joint and reduce the amount of tensile force placed on the ACL.[6,13] A common way to measure co-activation of the quadriceps and hamstrings is by calculating the H:Q ratio. H:Q ratios of 0.6 and greater have been reported to decrease the risk of hamstring and ACL injuries,[14] and ratios closer to 1 indicate higher activation of the hamstring muscles, which aids the ACL in providing additional passive resistance to anterior translation increasing the stability of the knee.[2,15] Therefore, H:Q ratios of greater than 0.6 are considered adequate, while those less than 0.6 are considered poor for this review. In order to reduce the risk of ACL injury, it is important to adequately train the hamstring muscles through exercises that produce adequate H:Q co-activation ratios.

Closed kinetic chain exercises (CKC) are important for functional movement patterns promoting co-activation of the quadriceps and hamstrings, and consequently are commonly used in training to prevent ACL injuries.[1,13] Compressive forces experienced during weight bearing add to the stability of the knee joint, which are not experienced during open chain kinetic exercises (OKC).[1,13,16] OKC encourage quadriceps dominance and promote increased tensile stress on the ACL.[16] During closed chain knee extension, external torques are largest from 90 to 45 degrees of knee flexion, with the greatest extensor moment arm occurring between 20 and 60 degrees of knee flexion. The greatest flexor moment arm occurs between 50 and 90 degrees of knee flexion.[4] CKC are commonly preferred to OKC in ACL prevention due to the combination of CKC tending to produce a higher H:Q ratio than OKC, as well as their functional strengthening benefits.

OBJECTIVES

Females are at an increased risk for ACL injuries partly due to the predominant activation of the quadriceps over the hamstrings, increasing the tensile strain on the ACL.[4] Many ACL injuries occur during closed chain activities, compared to open chain activities, due to the increased muscular control needed to stabilize the knee.[4] Therefore, CKC were chosen as the focus of this review. The purpose of this systematic review was to compare quadriceps and hamstring muscle activation during common closed kinetic chain therapeutic exercises in healthy female knees to determine what exercises are able to produce adequate H:Q co-activation ratios.

METHODS

Protocol and registration

The current systematic review was registered on PROSPERO (http://www.crd.york.ac.uk/PROSPERO/) with registration number: CRD42015029898.

Eligibility criteria

The following criteria were required for inclusion: 1) studies that assessed electromyography (EMG) activity in at least one quadriceps and one hamstring muscle, 2) studies that reported EMG activity for females, 3) studies where participants performed closed kinetic chain exercises, 4) studies that explicitly stated participants had healthy knees or no prior surgical history of the knee, 5) full-text articles available in English, and 6) human participants. Studies were excluded if they did not report female EMG activity separately from male data or if gender was not specified.

Information sources

PubMed, Scopus, CINAHL, SportDiscus, Web of Science, and PEDro electronic databases were searched in November 2015 and May 2016 for eligible articles relating to quadriceps and hamstrings EMG activity during exercise. A hand search was performed to complete the exhaustive search and include any other eligible articles.

Search

The search strategy for each searched database, approved by a Walsh University librarian, is listed in Appendix 1.

Study selection

All studies identified through the systematic search were retrieved and duplicates were removed. Two reviewers independently screened titles and abstracts for inclusion in the full-text review. A third party reviewer resolved any discrepancies. Full-text articles identified through the title and abstract screen were obtained and assessed by two independent reviewers for inclusion in the systematic review. A third party reviewer once again resolved any discrepancies.

Data collection process

Data collection was performed by two reviewers independently, and then cross-checked for accuracy. The participants' characteristics, the muscles studied, the exercises performed, and EMG activity of the quadriceps and hamstrings muscles were included in the review.

Data items

The following operational definitions were applied to studies for inclusion. Quadriceps was defined as one or more of the four quadriceps muscles (rectus femoris, vastus lateralis, vastus medialis, and/or vastus intermedius). Hamstrings was defined as any one of the muscles of the hamstring muscle group (biceps femoris, semitendinosus, and/or semimembranosus). The specific muscles researched in each study were noted when available. Closed kinetic chain exercises (CKC) were defined as exercises that involved weight-bearing where the distal segment was fixed against the ground.[13] In order to be considered as healthy, the article had to specifically denote that participants were healthy or had no surgical knee history. Mean EMG activity, % maximal voluntary isometric contraction (MVIC), and H:Q ratio was recorded for each muscle studied. H:Q ratios that were greater than 0.6 were considered adequate, while those that were less than 0.6 were considered poor.

Risk of bias in individual studies

Risk of bias in individual studies was assessed using the Mixed Methods Appraisal Tool (MMAT). Two screening questions require that the study have a clear objective and addressed the current research question. Four additional questions are used to determine the quality of the study based on study design. Each paper was rated as 25% (*), 50% (**), 75% (***), or 100% (****) based on one criteria to all four criteria being met, with a higher percentage indicating higher quality.[17] Quality assessment was performed independently by two reviewers, with disagreements being resolved by reaching a consensus.

Summary Measures

Primary outcome measures included %MVIC,[4] mean EMG data, and H:Q ratio for closed kinetic chain exercises. For articles where H:Q ratio was not provided, the ratio was calculated from the mean %MVIC or mean EMG data provided by dividing %MVIC or mean EMG of hamstring muscles by %MVIC or mean EMG of quadriceps muscles, respectively.

RESULTS

Study Selection

PubMed, SportDiscus, CINAHL, Scopus, Web of Science, and PEDro electronic searches acquired 982

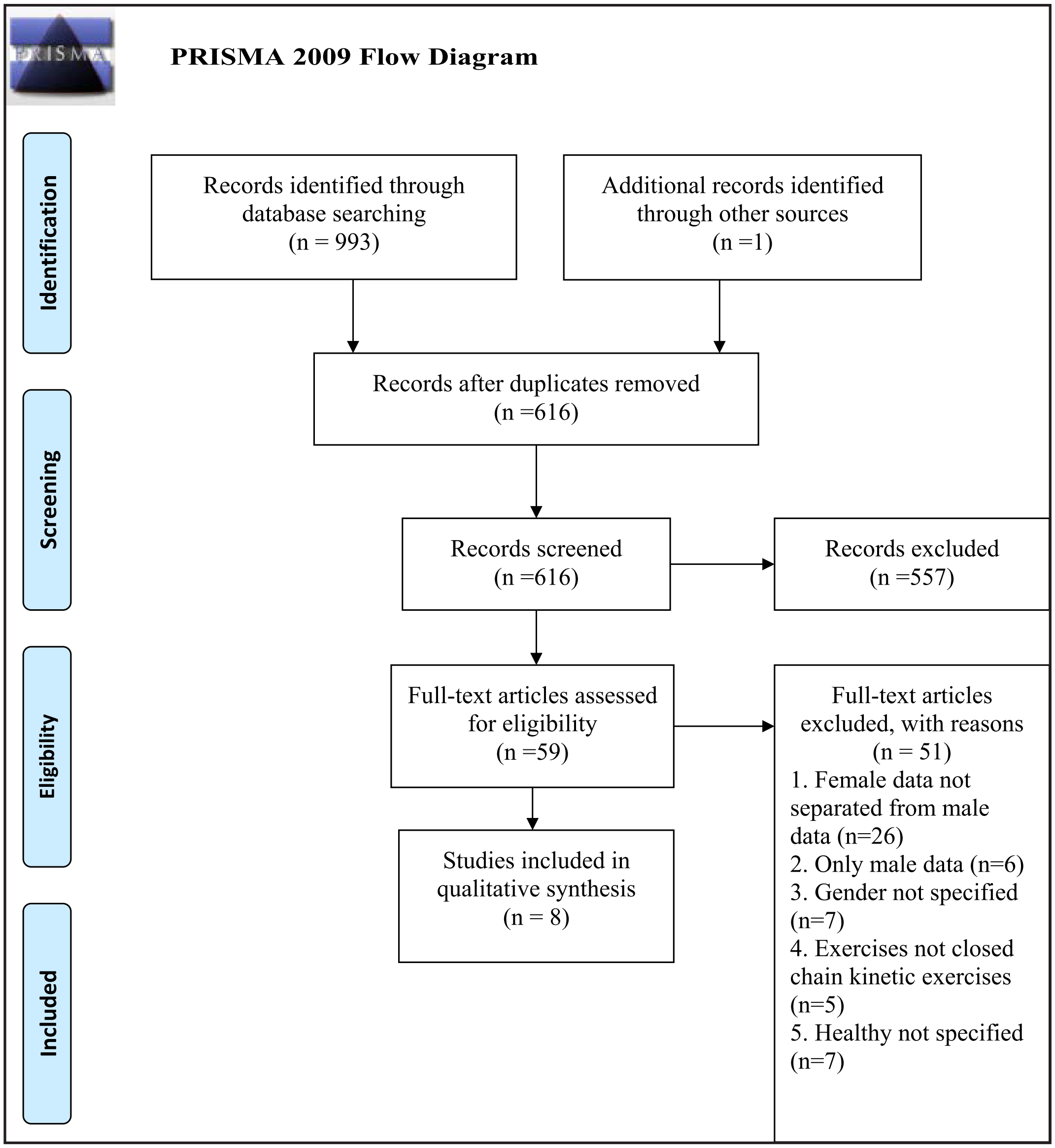

Figure 1.

articles to be screened for inclusion. After duplicates were removed, 605 articles remained for screening. The title and abstract screen excluded 546 articles, leaving 59 articles for full-text screen. Fifty-one articles were excluded. One article was identified through a hand search, leaving a total of eight articles to be included in the final review. See Figure 1 for details.

Study Characteristics

Eight studies were included for the final review. Number of participants, mean age, mean height, and mean weight can be found in Table 1. Seven studies tested the dominant lower extremity,[18-24] and one study[25] tested the right lower extremity. The primary outcome was mean EMG in three studies,[19,21,25] %MVIC in five studies,[18,20,22-24] and H:Q ratio in three studies.[18,22,23] H:Q ratio was calculated from mean % MVIC or mean EMG data by the authors, when not provided, in five studies.[19,20,21,24,25] A total of seven different CKC exercises were analyzed throughout the eight included studies. Four studies[20-22,25] used different variations of a two-legged squat and five studies[18,19,21,23,24] used variations of a single-legged squat. A lateral step-up was analyzed in two studies,[18,19] and the Fitter[18], Stairmaster®[18], and slide board[18] were all

Table 1. *Summary of Articles*								
Author, Year	**Female Participants (n)**	**Age (years)**	**Height (cm)**	**Weight (kg)**	**Muscles**	**Exercises**	**Lower Extremity Tested**	**Outcome**
Hopkins et. al., 1999	38	21.9 ± 2.8	166.9 ± 6.3	61.9 ± 8.5	Vastus lateralis Vastus medialis Biceps femoris	Unilateral one-quarter squat Lateral step-up	Dominant Lower Extremity	Mean EMG Activity
Blanpied, 1999	20	31.3 ± 6.9	160.9 ± 4.1	58.1 ± 8.7	Vastus lateralis Hamstrings muscle	Squat machine (foot forward and foot in line with hip & support at hip and scapular level)	Right Lower Extremity	Mean EMG Activity
Youdas et. al., 2007	15	24.4 ± 2.4	166.9 ± 7.1	63.5 ± 1.3	Rectus femoris Hamstrings muscle	Single-limb squat (stable and labile surface)	Dominant Lower Extremity	% MVIC H:Q Ratio
McCurdy et. al., 2010	11	20.63 ± 1.03	167.0 ± 11.00	59.37 ± 4.0	Rectus femoris Biceps femoris	Modified single-leg squat Two-leg squat	Dominant Lower Extremity	Mean EMG Activity
Graham et. al., 1993	10	21.0 ± 1.3	170.9 ± 4.4	68.1 ± 5.2	Rectus femoris Biceps femoris	Unilateral one-quarter squat Leg extensions on N-K table Lateral step-ups Fitter Stairmaster Slideboard	Dominant Lower Extremity	% MVIC Total EMG H:Q %
Nishiwaki et al., 2006	9	22.7 ± 2.3	160.0 ± 6.0	47.7 ± 1.5	Vastus medialis Semitendinosus Biceps femoris long head	Squat with COG over feet Squat with hands touching wall Wall squat	Dominant Lower Extremity	% MVIC H:Q (ST:VM) H:Q (BF:VM)
Lynn et. al., 2012	16				Rectus femoris Biceps femoris	Regular Squat Counterbalanced squat	Dominant Lower Extremity	% MVIC
Zeller et. al., 2003	9	20.00 ± 1.50	171.30 ± 6.10	64.36 ± 5.59	Rectus Femoris Vastus Lateralis Biceps Femoris	Single-Leg Squat	Dominant Lower Extremity	% MVIC

EMG= electromyography; MVIC= maximal voluntary isometric contraction; H:Q= hamstrings:quadriceps ratio; ST:VM = semitendinosus:vastus medialis; BF:VM= biceps femoris:vastus medialis

analyzed in one study. Placement of electrodes varied for each study, and muscles tested for each studied are described in Table 1.

Risk of Bias within Studies

Four studies[21,23,24,25] received an overall quality rating of three stars (***), and four studies[18-20,22] received an overall quality score of four stars (****) based on the MMAT criteria. Each of the four articles[21,23-25] receiving three stars was due to the participant selection not being representative of the whole population being studied. Participants were either required to be under 170 centimeters tall,[25] only Division I athletes,[21] only DPT students,[23] or only NAIA student-athletes.[24] Table 2 presents quality assessment details from each study.

Results of Individual Studies

Mean EMG activity, % MVIC, and H:Q ratios are presented in Tables 3, 4, and 5, respectively. All exercises produced higher mean EMG muscle activation in quadriceps muscles versus hamstring muscles except for the squat machine exercise with posterior support at the level of the scapula, and the feet located 50 cm in front of the hips (21.1 ± 13.1 vastus lateralis; 26.6 ± 9.9 hamstrings).[25] All exercises where % MVIC was reported, had higher quadriceps than hamstring activation (Table 4). The lowest % MVIC reported for the quadriceps was 25.9 ± 6.8 for the quarter squat,[18] and the greatest quadriceps activation (seen in the vastus lateralis) was with the single-leg squat (116.2 ± 73.5).[24] % MVIC values ranged from 9.2 ± 1.1 for the semitendinosus with

Table 2. *Quality Assessment*

Study	Screening Questions		Quantitative Descriptive Quality Criteria				
	Clear qualitative, quantitative, or mixed methods research objectives?	Collected data addresses research objectives?	Sampling strategy relevant to address question?	Sample representative of population understudy?	Appropriate measurements?	Acceptable response rate?	Overall Rating
Hopkins et. al., 1999	Y	Y	*	*	*	*	****
Blanpied, 1999	Y	Y		*	*	*	***
McCurdy et. al., 2010	Y	Y		*	*	*	***
Graham et. al., 1993	Y	Y	*	*	*	*	****
Nishiwaki et al., 2006	Y	Y	*	*	*	*	****
			Quantitative Non-randomized Quality Criteria				
			Selection bias minimized during participant recruitment?	Exposure/intervention and outcome measurements are appropriate?	Participants are comparable, or researchers control differences?	Complete outcome data, response rate or follow up rate?	Overall Rating
Lynn et. al., 2012	Y	Y	*	*	*	*	****
Youdas et. al., 2007	Y	Y		*	*	*	***
Zeller et. al., 2003	Y	Y		*	*	*	***

a squat with the center of gravity placed behind the feet from 0 to 30 degrees of knee flexion[22] to 41.3 ± 9.0 for a slide board exercise.[18] The quarter squat exercise produced H:Q ratios that ranged from 0.17[5] to 0.615.[18] The step-up exercise yielded similar H:Q ratios, ranging from 0.23[19] to 0.611.[18] A multitude of variations existed for the performance of the single-legged squat[21,23,24] as well as two-legged squat,[20-22,25] yielding a wide range of ratios. The Fitter (0.706), Stairmaster® (0.629), and slide board (0.739) H:Q ratios were only analyzed in one study.[18]

DISCUSSION

Summary of Evidence

Many exercises included in this review were performed either with variations of the same exercise across studies or were only included in one study, limiting comparisons and the ability to perform a meta-analysis. The exercises included a variety of two leg, single leg, barbell squat, and body weight exercises. Overall, two-legged squats demonstrated poor H:Q ratios, with nearly all two-legged squat variations producing ratios less than 0.6.[20-22,25] In two studies,[20,22] knee flexion was 90 degrees or greater during the squat exercise, and another study instructed participants to not allow knee translation past the toes.[21] The deep range of motion of these squat variations could possibly contribute to lower H:Q ratios. During the descent portion of the squat, quadriceps activity peaked between 80-90 degrees of knee flexion, due to the increased external torque from 45 to 90 degrees of closed chain knee flexion.[4,26] Hamstring activity peaks between 30-80 degrees of knee flexion during the ascent portion of the squat.[4,26] Hip angulation was not reported in these studies, but increased hip flexion during the squat increases hamstring activity and decreases tensile forces on the ACL.[26] Squats into deep ranges

Table 3. *Mean ± SD EMG Activity*

Study	Exercise	Quadriceps	Hamstring
Hopkins et. al, 1999*	Unilateral Quarter Squat (Flexion)	270.09 ± 129.4^{VM} 301.80 ± 200.8^{VL}	50.37 ± 31.5^{BF}
	Unilateral Quarter Squat (Extension)	140.20 ± 56.7^{VM} 162.30 ± 68.7^{VL}	54.96 ± 5.6^{BF}
	Lateral Step-Up (Flexion)	220.90 ± 83.8^{VM} 258.63 ± 115.4^{VL}	59.18 ± 27.6^{BF}
	Lateral Step-Up (Extension)	149.70 ± 50.8^{VM} 258.63 ± 115.4^{VL}	57.75 ± 30.7^{BF}
Blanpied et.al, 1999**	Squat Machine: Hip: I-L	22.8 ± 11.5^{VL}	4.5 ± 1.5^{HM}
	Squat Machine: Hip: FF	22.6 ± 13.1^{VL}	11.1 ± 5.6^{HM}
	Squat Machine: Scap: I-L	20.3 ± 12.5^{VL}	12.5 ± 5.6^{HM}
	Squat Machine: Scap: FF	21.1 ± 13.1^{VL}	26.6 ± 9.9^{HM}
	Wall Slide: Hip: I-L	22.0 ± 10.7^{VL}	6.7 ± 2.4^{HM}
	Wall Slide: Hip: FF	27.0 ± 13.2^{VL}	9.6 ± 3.6^{HM}
	Wall Slide: Scap: I-L	22.3 ± 11.9^{VL}	6.5 ± 2.3^{HM}
	Wall Slide: Scap: FF	26.0 ± 13.6^{VL}	12.0 ± 4.6^{HM}
McCurdy et. al, 2010***	Modified Single Leg Squat	70.6 ± 55.29^{RF}	57.10 ± 49.36^{BF}
	2 Leg Squat	105.44 ± 91.03^{RF}	22.95 ± 21.11^{BF}
Graham et. al, 1993****	Fitter	$0.06 \pm .01^{RF}$	$0.03 \pm .01^{BF}$
	Stairmaster	$0.04 \pm .01^{RF}$	$0.02 \pm .004^{BF}$
	Unilateral Quarter Squat	$0.08 \pm .01^{RF}$	$0.04 \pm .01^{BF}$
	Slide Board	$0.07 \pm .02^{RF}$	$0.03 \pm .02^{BF}$
	Lateral Step-Up	$0.06 \pm .02^{RF}$	$0.03 \pm .01^{BF}$

Note: Hip= support was located at hip level; Scap= support was located at the scapular level; I-L= the foot was in line with the hips; FF= the feet were located 50 cm in front of the line of the hip

* = values reported as EMG (mV x sec x 10^3); ** = values were not reported with a unit; ***= values were reported as EMG (mV); **** = values were reported as total EMG (mV X sec)

^{VM} indicates vastus medialis muscle; ^{VL} indicates vastus lateralis muscle; ^{BF} indicates biceps femoris muscle; ^{HM} indicates hamstring muscle group; ^{RF} indicates rectus femoris muscle;

reflected a quadriceps dominant exercise which can increase the tensile force on the ACL.

Two squat variations, the squat machine with support at the scapula and the feet in line with the hips, and the squat machine with support at the scapula and feet placed 50 cm in front of the hips, produced a H:Q ratio greater than 0.6.[25] In this study, only 60 degrees of knee flexion was allowed. The squat machine with support at the level of the scapula and the feet placed 50 cm in front of the hips was the only variation of the squat that did demonstrate a H:Q ratio (1.26) that favored the hamstrings. By providing support at the scapula versus the hip, the moment arm for ground reaction forces to the hip was greater than the moment arm for ground reaction force to the knee. This increased the activation needed from the hamstrings acting as hip extensors, rather than the knee extensors to provide stabilization during the exercise.[25] By placing the feet 50 cm forward as well, the moment arm for the hip remains greater than the moment arm for the knee. This further contributes to the need of the hamstrings to work as hip extensors, causing more activation of the hamstrings than the quadriceps.[25]

Variations of the single-leg squat show promise as an exercise that produces an adequate H:Q ratio with some variations producing ratios greater than 0.6. Zeller et al and Hopkins et al both had poor H:Q ratios for a single-leg squat which may be attributed to the depth of the squat. Participants in the Zeller et al study were instructed to squat down as far as possible without losing their balance, and averaged

Table 4. *Percent Maximal Voluntary Isometric Contraction (% MVIC ± SD)*

Study	Exercise	Quadriceps	Hamstring
Youdas et. al, 2007	Single Leg Squat (Stable)	33.9^{RF}	
	Single Leg Squat (Labile)		19.9^{HM}
Graham et. al, 1993	Fitter	38.5 ± 17.4^{RF}	27.2 ± 11.1^{BF}
	Stairmaster	36.0 ± 19.7^{RF}	22.6 ± 10.6^{BF}
	Unilateral Quarter Squat	25.9 ± 6.8^{RF}	15.9 ± 6.4^{BF}
	Slide Board	55.8 ± 27.3^{RF}	41.3 ± 9.0^{BF}
	Lateral Step-Up	40.9 ± 9.9^{RF}	25.0 ± 8.0^{BF}
Nishiwaki et. al, 2006	Squat: CGO: 0-30	47.6 ± 1.9^{VM}	12.4 ± 2.2^{BF} 9.9 ± 1.4ST
	Squat: CGO: 30-60	62.5 ± 2.1^{VM}	15.3 ± 2.3^{BF} 11.1 ± 1.1ST
	Squat: CGO: 60-90	70.2 ± 1.8^{VM}	16.3 ± 2.8^{BF} 11.8 ± 1.8ST
	Squat: CGF: 0-30	44.3 ± 1.5^{VM}	11.5 ± 1.2^{BF} 9.4 ± 1.6ST
	Squat: CGF:30-60	54.7 ± 1.8^{VM}	13.9 ± 1.9^{BF} 11.4 ± 1.8ST
	Squat: CGF: 60-90	61.2 ± 1.6^{VM}	14.6 ± 1.8^{BF} 11.8 ± 1.3ST
	Squat: CGB: 0-30	37.7 ± 2.1^{VM}	10.3 ± 2.5^{BF} 9.2 ± 1.1ST
	Squat: CGB: 30-60	47.6 ± 1.6^{VM}	13.2 ± 2.4^{BF} 11.5 ± 1.5ST
	Squat: CGB: 60-90	52.0 ± 2.4^{VM}	15.4 ± 2.8^{BF} 11.9 ± 1.8ST
Lynn et. al, 2012	Squat	71.3 ± 51.5^{RF}	28.9 ± 27.0^{BF}
	Counter-balanced Squat	64.5 ± 45.0^{RF}	30.5 ± 28.9^{BF}
Zeller et. al, 2003	Single-Leg Squat	116.2 ± 73.5^{VL} 83.4 ± 14.5^{RF}	24.5 ± 11.4^{BF}

Note: CGO= the center of gravity was over the feet; CGF= the center of gravity was in front of the feet; CGB= the center of gravity was behind the feet; ^{VM} indicates vastus medialis muscle; ^{VL} indicates vastus lateralis muscle; ^{BF} indicates biceps femoris muscle; ^{HM} indicates hamstring muscle group; ^{RF} indicates rectus femoris muscle; ST indicates semitendinsous muscle group

approximately 95 degrees of knee flexion,[24] while participants in the Hopkins et al study only performed the single-leg squat to about 30 degrees of knee flexion.[19] Performing a squat past 90 degrees may favor the quadriceps due to the increased external torque, while squatting only to 30 degrees does not allow the hamstrings to have optimal activation since the moment arm of the hamstrings is greatest from 50 to 90 degrees of knee flexion.[4] Two studies, Youdas et al and Graham et al, performed variations of the single leg squat that produced H:Q ratios that were greater than 0.6. Participants in the Youdas et. al study averaged approximately 45 degrees of knee flexion, while those in the Graham et al study averaged about 56 degrees of knee flexion. Youdas et al also encouraged forward trunk lean while performing the single-leg squat to increase tension on the hamstrings. This demonstrates that the degree of hip and knee flexion may play an important role in producing H:Q ratios that are considered appropriate, and not excessively quadriceps dominant.

Lateral step ups, performed in two studies,[18,19] presented a similar situation as single-leg squats. Those performed with a 20.3 cm step with an average degree of knee flexion of 68.5 degrees, produced a H:Q ratio of 0.611,[18] while those performed with a 10 cm step and an average knee flexion of 30 degrees, only pro-

Table 5. *Hamstring: Quadriceps Ratio (H:Q)*

Study	Exercise	H:Q
Hopkins et. al, 1999	Unilateral Quarter Squat (Flexion)	0.17 BF/VL
	Unilateral Quarter Squat (Extension)	0.34 BF/VL
	Unilateral Quarter Squat (Flexion)	0.19 BF/VM
	Unilateral Quarter Squat (Extension)	0.39 BF/VM
	Lateral Step-Up (Flexion)	0.23 BF/VL
	Lateral Step-Up (Extension)	0.36 BF/VL
	Lateral Step-Up (Flexion)	0.27 BF/VM
	Lateral Step-Up (Extension)	0.39 BF/VM
Blanpied et. al, 1999	Squat Machine: Hip: I-L	0.20
	Squat Machine: Hip: FF	0.49
	Squat Machine: Scap: I-L	0.62
	Squat Machine: Scap: FF	1.26
	Wall Slide: Hip: I-L	0.30
	Wall Slide: Hip: FF	0.36
	Wall Slide: Scap: I-L	0.29
	Wall Slide: Scap: FF	0.46
Youdas et. al, 2007	Single Leg Squat (Stable)	0.62
	Single Leg Squat (Labile)	0.71
McCurdy et. al, 2010	Modified Single Leg Squat	0.81
	2 Leg Squat	0.22
Graham et. al, 1993	Fitter	0.706
	Stairmaster	0.629
	Unilateral Quarter Squat	0.615
	Slide Board	0.739
	Lateral Step-Up	0.611
Nishiwaki et. al, 2006	Squat: CGO: 0-30*	0.19 ± 1.3
	Squat: CGO: 30-60*	0.15 ± 1.5
	Squat: CGO: 60-90*	0.12 ± 1.2
	Squat: CGF: 0-30*	0.20 ± 1.4
	Squat: CGF:30-60*	0.15 ± 1.3
	Squat: CGF: 60-90*	0.14 ± 1,5
	Squat: CGB: 0-30*	0.26 ± 1.8
	Squat: CGB: 30-60*	0.20 ± 1.7
	Squat: CGB: 60-90*	0.18 ± 1.2
	Squat: CGO: 0-30**	0.26 ± 1.5
	Squat: CGO: 30-60**	0.24 ± 1.3
	Squat: CGO: 60-90**	0.23 ± 1.7
	Squat: CGF: 0-30**	0.26 ± 1.6
	Squat: CGF:30-60**	0.26 ± 1.5
	Squat: CGF: 60-90**	0.24 ± 1.4
	Squat: CGB: 0-30**	0.27 ± 1.2
	Squat: CGB: 30-60**	0.28 ± 1.4
	Squat: CGB: 60-90**	0.30 ± 1.3
Lynn et. al, 2012	Squat	0.41
	Counter-balanced Squat	0.47
Zeller et. al, 2003	Single-Leg Squat	0.21 BF/VL
	Single-Leg Squat	0.29 BF/RF

Note: H:Q= Hamstrings:Quadricpes; BF/VL= Biceps Femoris/Vastus Lateralis; BF/VM= Biceps Femoris/Vastus Medialis; BF/RF= Biceps Femoris/Rectus Femoris; CGO= the center of gravity was over the feet; CGF= the center of gravity was in front of the feet; CGB= the center of gravity was behind the feet; * = Semitendinosus/Vastus Medialis Ratio; ** = Biceps Femoris/Vastus Medialis Ratio

duced H:Q ratios between 0.23 and 0.39.[19] This demonstrated the influence of hip and knee flexion angles to produce a H:Q ratio greater than 0.6.

The modified single leg squat[21] produced a H:Q ratio that is considered to be adequate. Participants in this study were instructed not to allow their knee to translate over their toes. During the modified single leg squat, the non-dominant leg was placed on a 12 inch step, which allowed for some weight bearing through both lower extremities. It also allowed for the center of gravity to move posterior to that of a regular single-leg squat, increasing the demand placed on the hamstrings.

The Fitter, Stairmaster®, and slide board exercises all produced H:Q ratios that were greater than 0.6 indicating good co-activation of the hamstrings and quadriceps.[18] Average degrees of knee flexion were 42 degrees for the Fitter, 72 degrees for the Stairmaster®, and 55 degrees for the slide board.

The comparison of these exercises demonstrate the importance of the degree of knee flexion while performing CKC in order to produce H:Q ratios that are not disproportionately quadriceps dominant. The results of these studies suggest that approximately 42 to 72 degrees of knee flexion may be the optimal range to encourage adequate H:Q co-activation ratios to reduce tensile force on the ACL and reduce the risk of injury. This can be in part because the hamstring moment arm is greatest between 50 and 90 degrees of knee flexion, and the quadriceps moment arm is greatest between 20 and 60 degrees of knee flexion with the external torque being greatest from 45 to 90 degrees of knee flexion. Not allowing for excessive knee flexion may diminish the need for eccentric control of the hamstrings to slow knee flexion, while too much knee flexion increases the external torque placed on the knee, both contributing to quadriceps dominant activation patterns. Exercises that produce poor H:Q ratios may be best avoided during the early rehabilitation phase after knee injury, or when the goal of rehabilitation is to promote hamstring activation.

Limitations

The primary limitation of this review was the small variety of exercises that were studied and the multiple variations of the same exercise that were performed across research studies. Some H:Q ratios were calculated based on average %MVIC that was presented in the studies, and not by the original researchers, which may contribute to slight variations in actual H:Q ratios. Another limitation was the inability to include studies that did not separate male and female data. Finally, only studies that were available in English could be included for review. Further research is needed to analyze H:Q ratios in other common therapeutic exercises that utilize CKC.

CONCLUSIONS

There are a variety of exercises that are performed to promote quadriceps and hamstring muscle strengthening. Multiple factors, including hormonal, anatomical, and neuromuscular, contribute to which exercise is preferred to produce a H:Q ratio that is above 0.6 in order to avoid excessive quadriceps dominance and anterior tensile force on the ACL. These results suggest that exercises with an appropriate range of motion, approximately 42 to 72 degrees, may yield adequate H:Q co-activation ratios and may decrease tensile load on the ACL as described in previous literature.

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APPENDIX 1. DETAILS OF SEARCH STRATEGY

PubMed Search Strategy

1. hamstrings[Text Word]
2. hamstring[Text Word]
3. hamstrings muscle[Text Word]
4. hamstring muscle[Text Word]
5. 1 OR 2 OR 3 OR 4
6. quadriceps muscle[MeSH Terms]
7. quadriceps muscle[Text Word]
8. quadricep muscle[Text Word]
9. quadriceps[Text Word]
10. quadricep[Text Word]
11. 6 OR 7 OR 8 OR 9 OR 10
12. electromyography[MeSH Terms]
13. electromyography[Text Word]
14. EMG[Text Word]
15. muscle activation[Text Word]
16. neuromuscular activation[Text Word]
17. co-activation[Text Word]
18. coactivation[Text Word]
19. co-recruitment[Text Word]
20. corecruitment[Text Word]
21. co-contraction[Text Word]
22. cocontraction[Text Word
23. h/q[Text Word]
24. h/q ratio[Text Word]
25. h/q activation[Text Word]
26. h/q coactivation
27. MVIC[Text Word]

28. maximal voluntary isometric contraction[Text Word]
29. maximum voluntary isometric contraction[Text Word]
30. 12 OR 13 OR 14 OR 15 OR 16 OR 17 OR 18 OR 19 OR 20 OR 21 OR 22 OR 23 OR 24 OR 25 OR 26 OR 27 OR 28 OR 29
31. resistance training[MeSH Terms]
32. resistance training[Text Word]
33. therapeutic exercise[Text Word]
34. muscle strengthening[Text Word]
35. exercise therapy[MeSH Terms]
36. exercise therapy[Text Word]
37. physical therapy[Text Word]
38. physiotherapy[Text Word]
39. exercise[MeSH Terms]
40. open chain kinetic exercise[Text Word]
41. closed chain kinetic exercise[Text Word]
42. 31 OR 32 OR 33 OR 34 OR 35 OR 36 OR 37 OR 38 OR 39 OR 40 OR 41
43. 5 AND 11 AND 30 AND 42

CINAHL Search Strategy

1. (MH "Hamstring Muscles") OR "hamstrings" OR "hamstring" OR "hamstring muscle" OR "hamstrings muscle"
2. (MH "Quadriceps Muscles+") OR "quadriceps" OR "quadricep" OR "quadricep muscle" OR "quadriceps muscle"
3. (MH "Electromyography") OR "electromyography" OR "EMG" OR "muscle activation" OR "neuromuscular activation" OR "co-activation" OR "coactivation" OR "co-recruitment" OR "corecruitment" OR "co-contraction" OR "cocontraction" OR "h/q" OR " h/q ratio" OR "MVIC" OR "Maximal voluntary isometric contraction" OR "maximum voluntary isometric contraction"
4. (MH "Resistance Training") OR "resistance training" OR (MH "Therapeutic Exercise") OR "therapeutic exercise" OR (MH "Closed Kinetic Chain Exercises") OR (MH "Lower Extremity Exercises") OR (MH "Muscle Strengthening+") OR "muscle strengthening" OR (MH "Open Kinetic Chain Exercises") OR "exercise therapy" OR (MH "Physical Therapy") OR "Physical therapy" OR "physiotherapy" OR (MH "Exercise") OR "closed kinetic chain" OR "closed chain" OR "open kinetic chain" OR "open chain"
5. 1 AND 2 AND 3 AND 4

Web of Science Search Strategy

1. TOPIC: (hamstrings) OR TOPIC: (hamstring) OR TOPIC: (hamstring muscle) OR TOPIC: (hamstrings muscle)
2. TOPIC: (quadriceps) OR TOPIC: (quadricep) OR TOPIC: (quadriceps muscle) OR TOPIC: (quadricep muscle)
3. TOPIC: (electromyography) OR TOPIC: (EMG) OR TOPIC: (muscle activation) OR TOPIC: (neuromuscular activation) OR TOPIC: (co-activation) OR TOPIC: (coactivation) OR TOPIC: (co-recruitment) OR TOPIC: (corecruitment) OR TOPIC: (co-contraction) OR TOPIC:(cocontraction) OR TOPIC: (h/q) OR TOPIC: (h/q ratio) OR TOPIC: (h/q activation) OR TOPIC: (h/q coactivation) OR TOPIC: (MVIC) ORTOPIC: (maximum voluntary isometric contraction) OR TOPIC: (maximal voluntary isometric contraction)
4. TOPIC: (resistance training) OR TOPIC: (therapeutic exercise) OR TOPIC: (muscle strengthening) OR TOPIC: (exercise therapy) OR TOPIC:(physical therapy) OR TOPIC: (physiotherapy) OR TOPIC: (exercise) OR TOPIC: (closed chain kinetic exercise) OR TOPIC: (open chain kinetic exercise)
5. 1 AND 2 AND 3 AND 4

Scopus Search Strategy

1. ((TITLE-ABS-KEY (quadriceps*)) OR (TITLE-ABS-KEY (quadriceps femoris*)) OR (TITLE-ABS-KEY (quads*)) OR (TITLE-ABS-KEY (quad*)) OR (TITLE-ABS-KEY (quadricep*)))
2. ((TITLE-ABS-KEY (hamstrings*)) OR (TITLE-ABS-KEY (hamstring*)))
3. ((TITLE-ABS-KEY (resistance training) OR TITLE-ABS-KEY (open chain kinetic exercise) OR TITLE-ABS-KEY (closed chain kinetic exercise) OR TITLE-ABS-KEY (therapeutic

exercise) OR TITLE-ABS-KEY (lower extremity exercise) OR TITLE-ABS-KEY (muscle strengthening) OR TITLE-ABS-KEY (neuromuscular facilitation) OR TITLE-ABS-KEY (plyometrics) OR TITLE-ABS-KEY (exercise therapy) OR TITLE-ABS-KEY (physical therapy) OR TITLE-ABS-KEY (physiotherapy) OR TITLE-ABS-KEY (neuromuscular activation)))

4. ((TITLE-ABS-KEY (electromyography) OR TITLE-ABS-KEY (emg) OR TITLE-ABS-KEY (electromyography feedback)))
5. 1 AND 2 AND 3 AND 4

PEDro Search Strategy

1. Knee EMG

SportDiscus Search Strategy

1. DE “QUADRICEPS muscle” OR DE “RECTUS femoris muscle” OR DE “VASTUS medialis”
2. DE “HAMSTRING muscle”
3. H/Q
4. H/Q ratio
5. H/Q activation
6. H/Q coactivation
7. DE “ELECTROMYOGRAPHY”
8. maximal voluntary isometric contraction
9. maximum voluntary isometric contraction
10. mvic
11. EMG
12. Muscle activation
13. Neuromuscular activation
14. Co-activation
15. Coactivation
16. Co-recruitment
17. Corecruitment
18. Co-contraction
19. Cocontraction
20. 3 OR 4 OR 5 OR 6 OR 7 OR 8 OR 9 OR 10 OR 11 OR 12 OR 13 OR 14 OR 15 OR 16 OR 17 OR 18 OR 19
21. DE “EXERCISE” OR DE “AEROBIC exercises” OR DE “ANAEROBIC exercises” OR DE “AQUATIC exercises” OR DE “BUTTOCKS exercises” OR DE “CALISTHENICS” OR DE “CHAIR exercises” OR DE “CIRCUIT training” OR DE “EXERCISE for children” OR DE “EXERCISE for girls” OR DE “EXERCISE for men” OR DE “EXERCISE for middle-aged persons” OR DE “EXERCISE for women” OR DE “EXERCISE for youth” OR DE “EXERCISE therapy” OR DE “FOOT exercises” OR DE “GYMNASTICS” OR DE “HIP exercises” OR DE “ISOKINETIC exercise” OR DE “ISOLATION exercises” OR DE “ISOMETRIC exercise” OR DE “ISOTONIC exercise” OR DE “KNEE exercises” OR DE “LEG exercises” OR DE “MUSCLE strength” OR DE “STRENGTH training”
22. closed kinetic chain
23. closed chain
24. open kinetic chain exercises
25. open kinetic chain
26. open chain
27. therapeutic exercise
28. muscle strengthening
29. DE “PHYSICAL therapy”
30. Physical therapy
31. physiotherapy
32. 21 OR 22 OR 23 OR 24 OR 25 OR 26 OR 27 OR 28 OR 29 OR 30 OR 31
33. 1 AND 2 AND 20 AND 32